eRHIC Detector Requirements and R&D Needs

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Contents of the talk

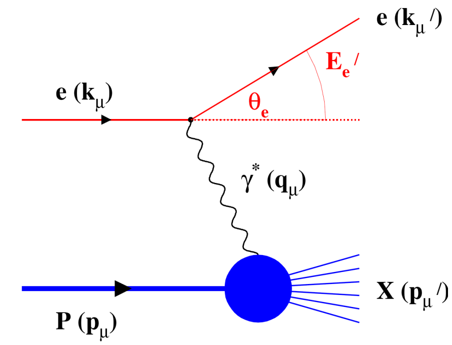
- EIC physics overview in one slide
- Short summary of detector requirements

- Detailed considerations for several selected topics
- Connection to EIC R&D where appropriate

EIC physics program overview

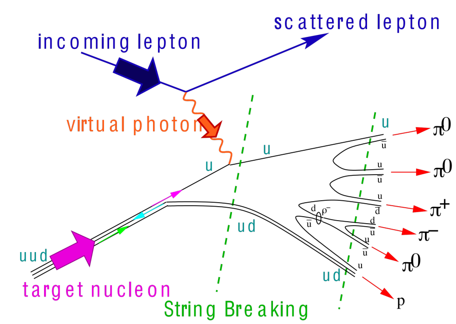
Inclusive Reactions in ep/eA:

- Physics: Structure Functions: g_1, F_2, F_L
- → Very good scattered electron ID
- → High energy and angular resolution of e' (defines kinematics $\{x,Q^2\}$)



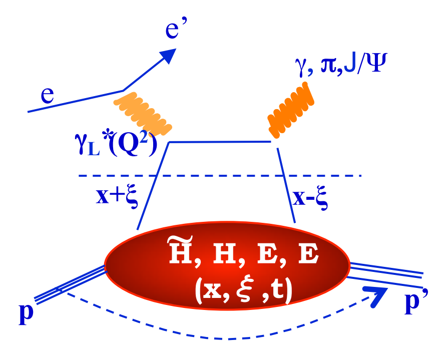
Semi-inclusive Reactions in ep/eA:

- Physics: TMDs, Helicity PDFs, FFs (with flavor separation); di-hadron correlations; Kaon asymmetries, cross sections; etc
- → Excellent hadron ID: $p^\pm$,$K^\pm$,$p^\pm$ separation over a wide $\{p, \eta\}$ range
- → Full Φ-coverage around γ^*, wide p_t coverage (TMDs)
- → Excellent vertex resolution (Charm, Bottom separation)



Exclusive Reactions in ep/eA:

- Physics: DVCS, exclusive VM production (GPDs; parton imaging in b_T)
- → Exclusivity (large rapidity coverage; reconstruction of all particles in a given event)
- → High resolution, wide coverage in t → Roman pots
- → (eA): veto nucleus breakup, determine impact parameter of collision
  → Sufficient acceptance for neutrons in ZDC



Detector and IR requirements "short list"

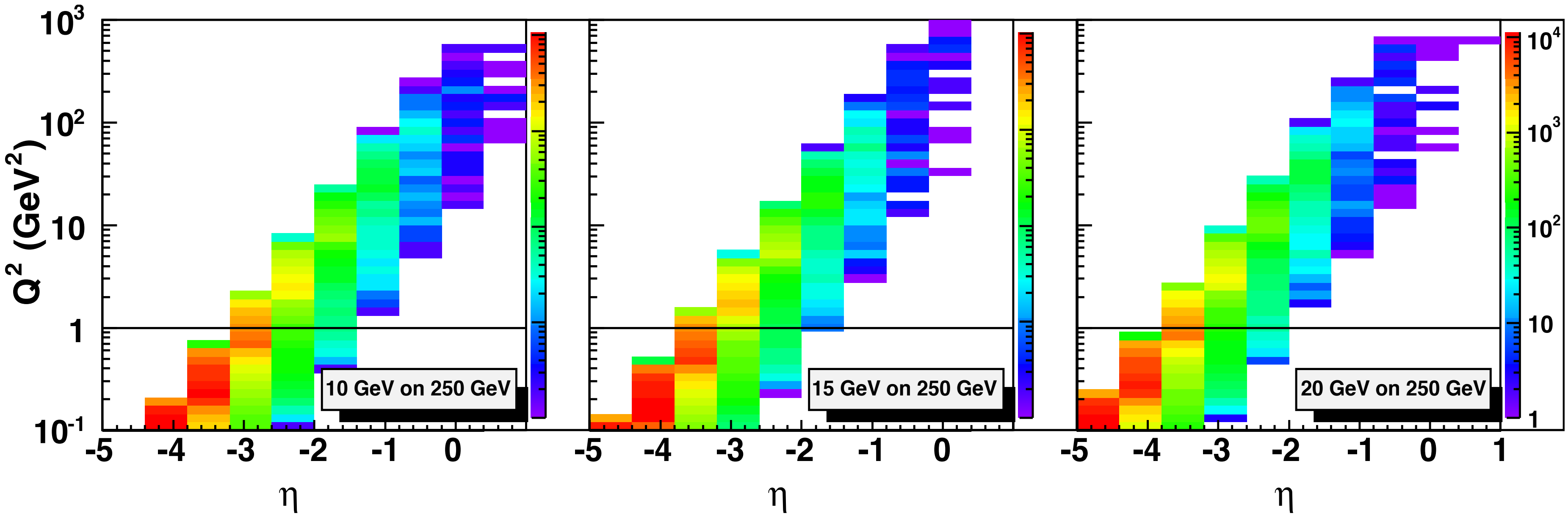
▪ The more close to 4π acceptance the better	→ hermetic coverage, but which η range?
▪ Low material budget	→ what is "low"?
▪ Reasonably high momentum resolution	→ how high is "high enough"?
▪ Reliable electron ID	→ η range?; which suppression factors?
▪ Good π/K/p separation	→ η range?; and again, how good?
▪ High spatial resolution of primary vertex	→ any numbers?
▪ *Ability to reconstruct jets*	→ which jets EIC detector will see?

- Close-to-beam-line acceptance detectors in order to register:
  - recoil protons
  - low Q^2 electrons
  - neutrons in hadron going direction
- Luminosity and polarization measurement

} acceptance
performance
IR interface
backgrounds

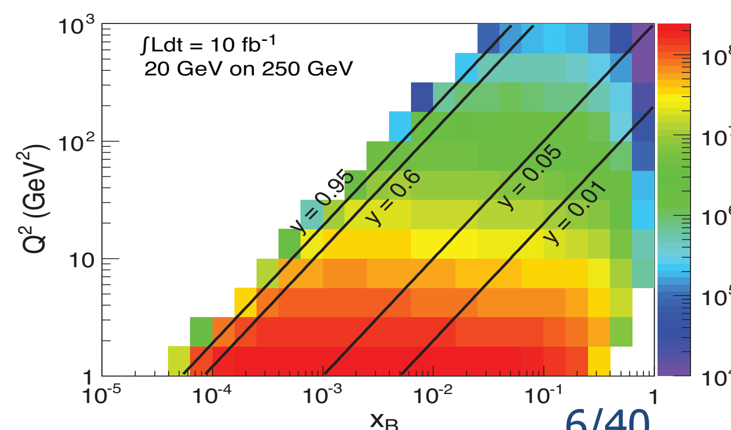
Acceptance considerations

Scattered lepton kinematics



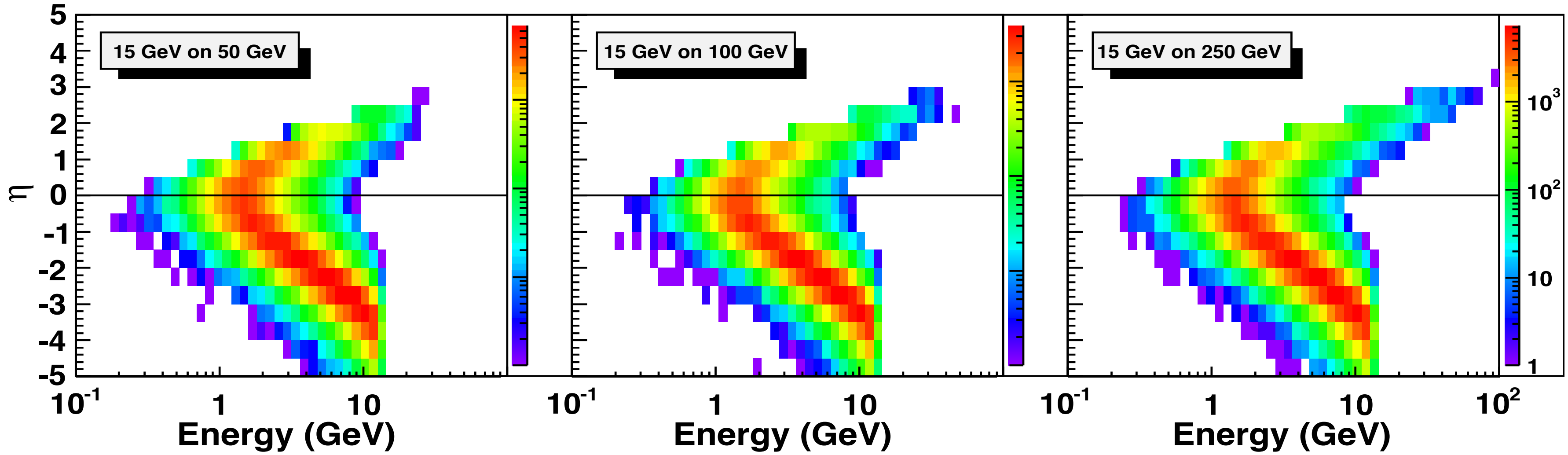
$Q^2 > 1.0$ GeV^2: rapidity coverage $-4 < \eta < 1$ is sufficient
$Q^2 < 0.1$ GeV^2: a dedicated low-Q^2 tagger is required anyway

Also notice: as lepton beam energy goes up scattered lepton is boosted to negative η



DVCS photon kinematics

Cuts: Q^2>1 GeV, 0.01<y<0.85

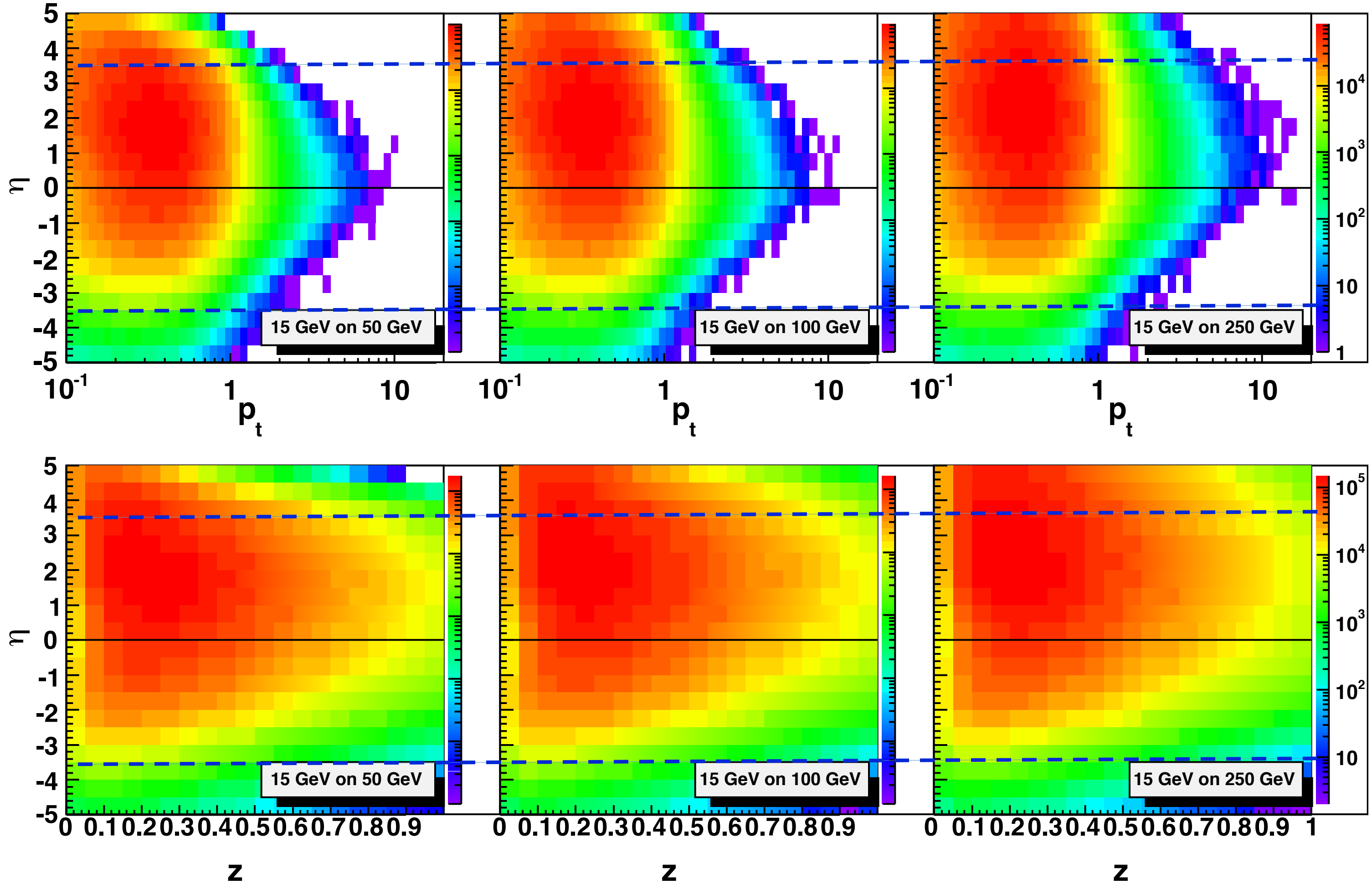


EmCal pseudo-rapidity coverage -4 < η < 1 is sufficient

Also notice: increasing hadron beam energy influences max. photon energy at fixed η – photons are boosted to negative rapidities (lepton direction)

SIDIS: kinematic coverage for pions

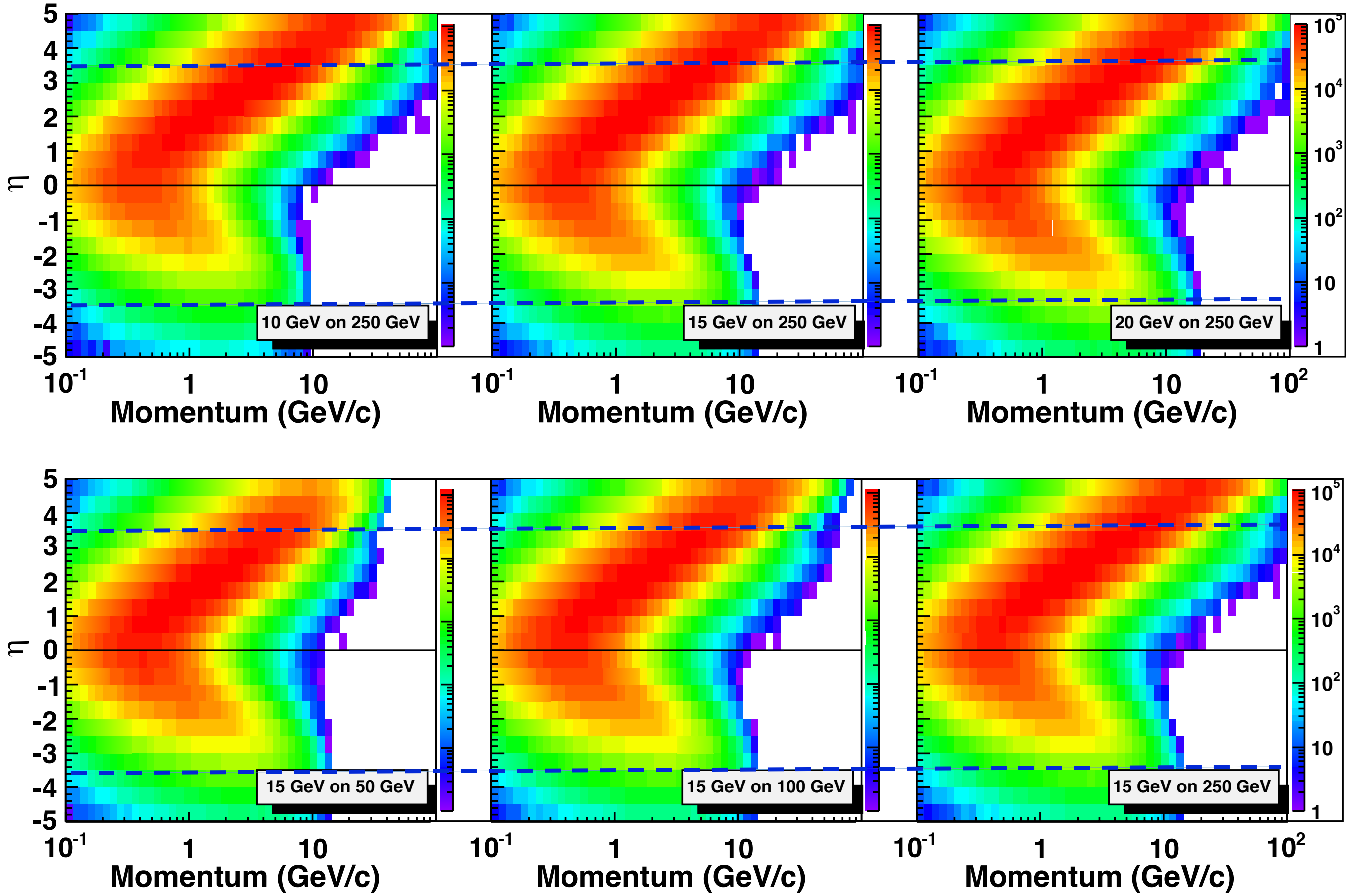
Cuts: Q^2>1 GeV^2, 0.01<y<0.95, p>1GeV (no difference between $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$)



$-3.5 < \eta < 3.5$ covers entire kinematic region in p_t & z important for physics

SIDIS: kinematic coverage for pions

Cuts: $Q^2>1$ GeV^2, $0.01<y<0.95$, $z>0.1$ ($\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$ look similar)



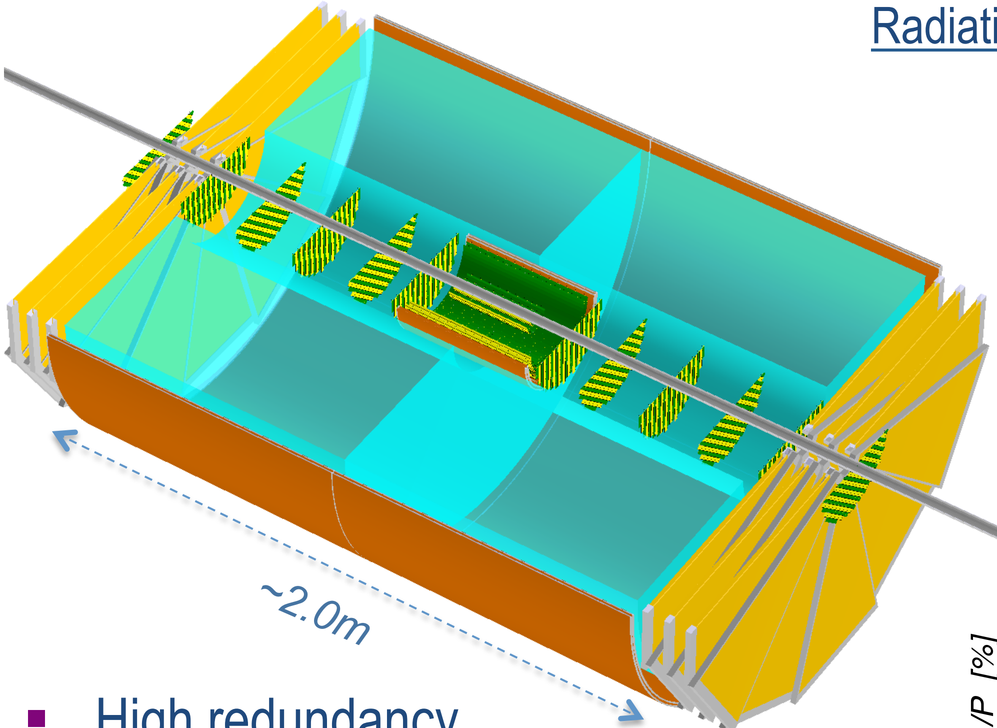
Increasing lepton beam energy boosts hadrons more to negative rapidity

Increasing hadron beam energy influences max. hadron energy at fixed η

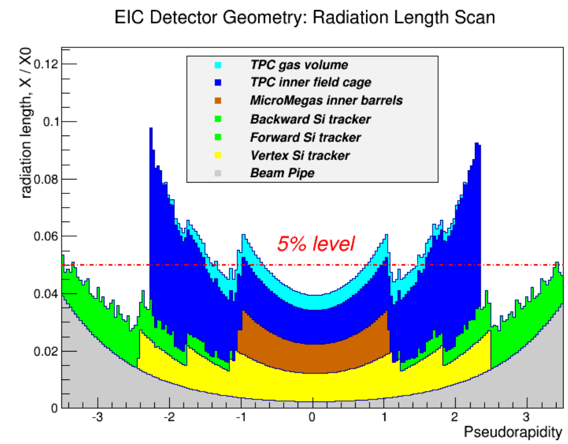
except for the highest η values ($1.5 < \eta < 3.5$ range) π/K/p separation below ~5 GeV/c or so is sufficient

Scattered lepton track reconstruction

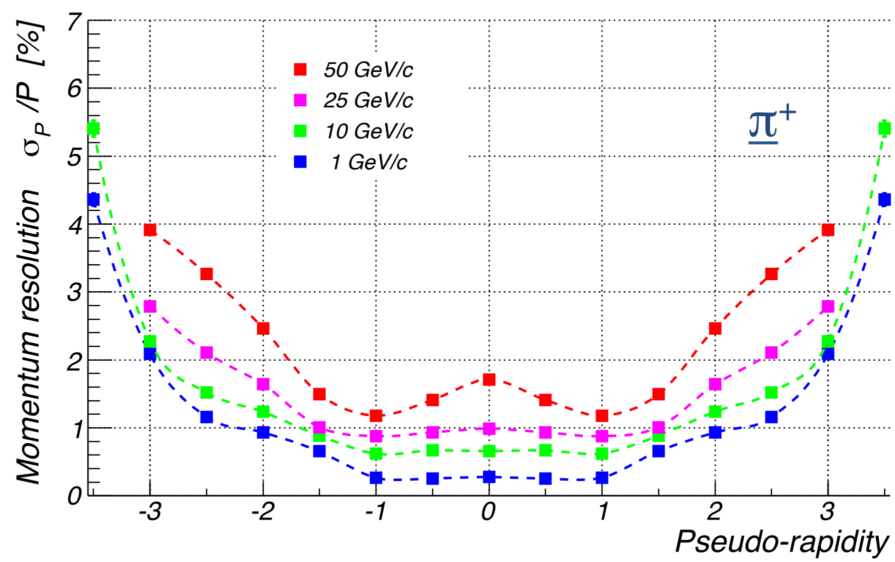
Reference tracker performance



Radiation length scan (inner tracking elements only)



Momentum resolution



- High redundancy
- Material budget ~5% rad.length or so
- Pretty much "basic" components

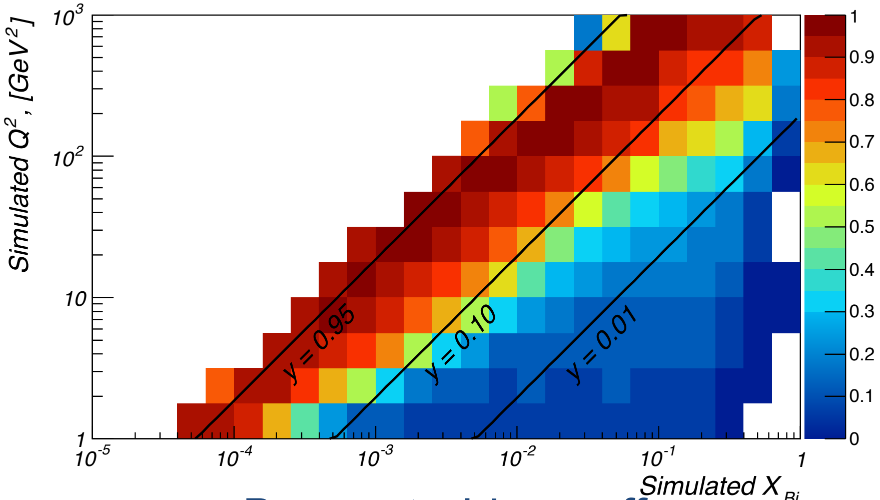
→H1 : 0.6%*P_t + 1.5%
→ZEUS : 0.5%*P_t + 1.5%

“Purity” in (x,Q^2) kinematic bins

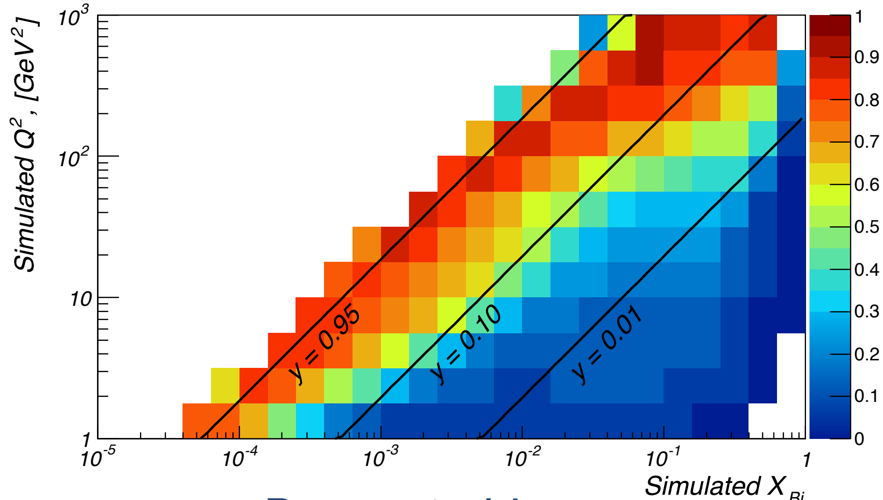
$$Purity = \frac{N_{gen} - N_{out}}{N_{gen} - N_{out} + N_{in}}$$

- Describes migration between kinematic bins
- Important to keep it close to 1.0 for successful unfolding

- {PYTHIA 20x250 GeV} -> {GEANT} -> {Kalman filter track fit}
- {x,Q^2} reconstructed through scattered lepton track parameters only



Bremsstrahlung off



Bremsstrahlung on

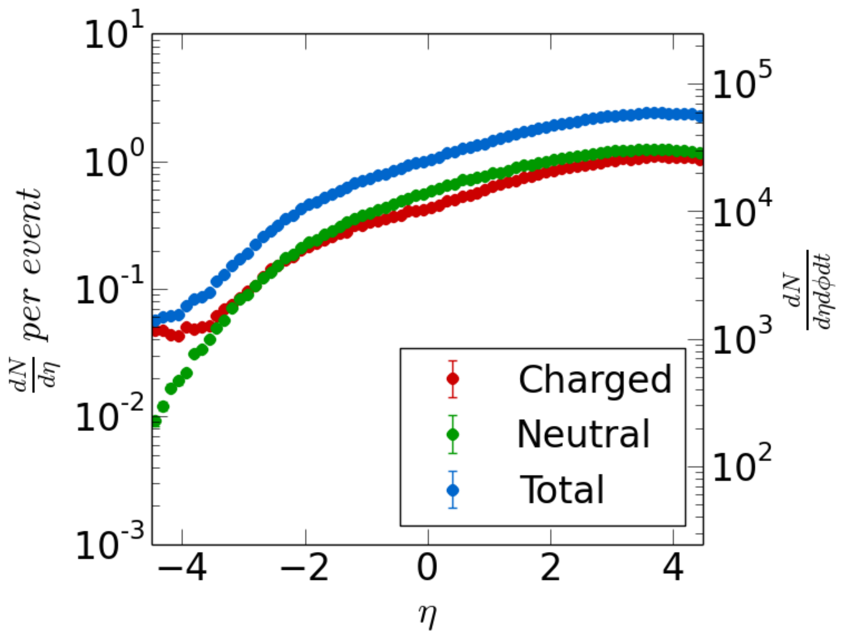
- Anticipated tracker does its job well enough (except for Y<0.1 region)
- Harmful effect of bremsstrahlung is clearly visible even at 5% rad.length

a hypothetic tracker with ~10-20% rad.length material budget is not really worth consideration

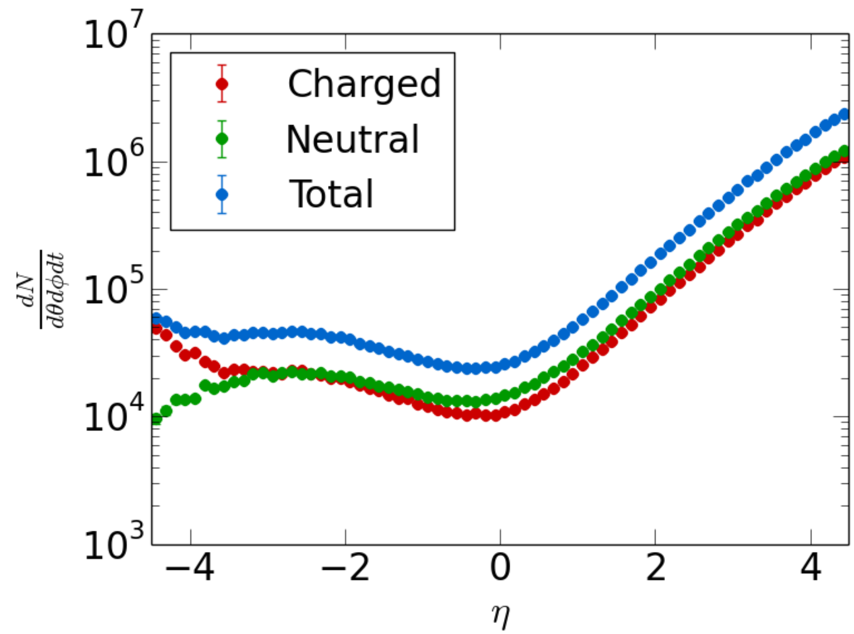
Particle yields

Interaction rate & absolute yields

PYTHIA 20x250 GeV configuration; absolute particle yields for L=10^{33} cm^{-2} s^{-1}



Per unit of {η,φ}



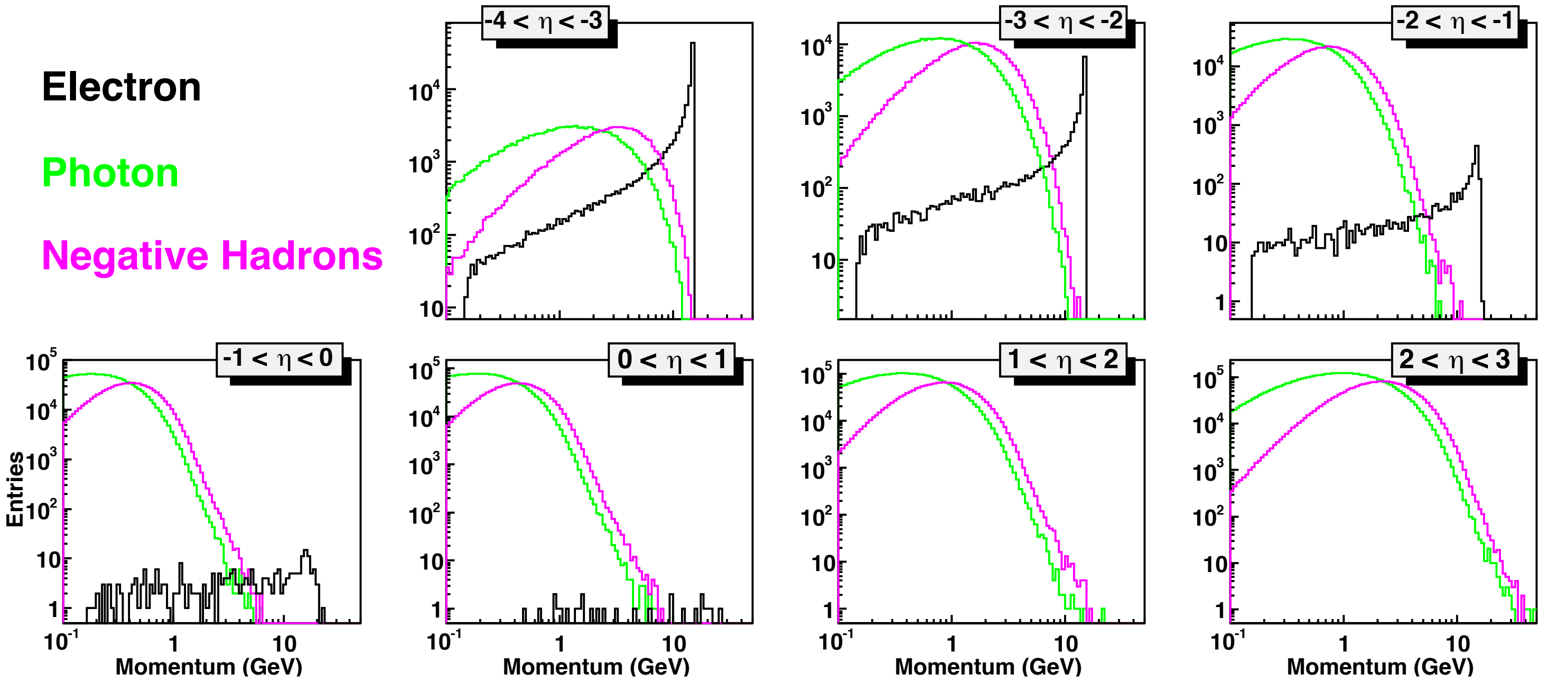
Per unit of {θ,φ}

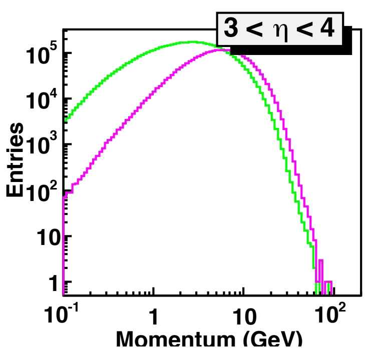
- Interaction rate ~50kHz (so 1:200 at ~10MHz bunch crossing frequency)
- At most few particles per unit of η per event
- Correspondingly low particle fluxes per unit of time

Not even close to LHC-HL upgrade (to say the least)

Relative electron/photon/h^- yields

15x250 GeV configuration; particle yields versus momentum in the 4 < η < 4 range:



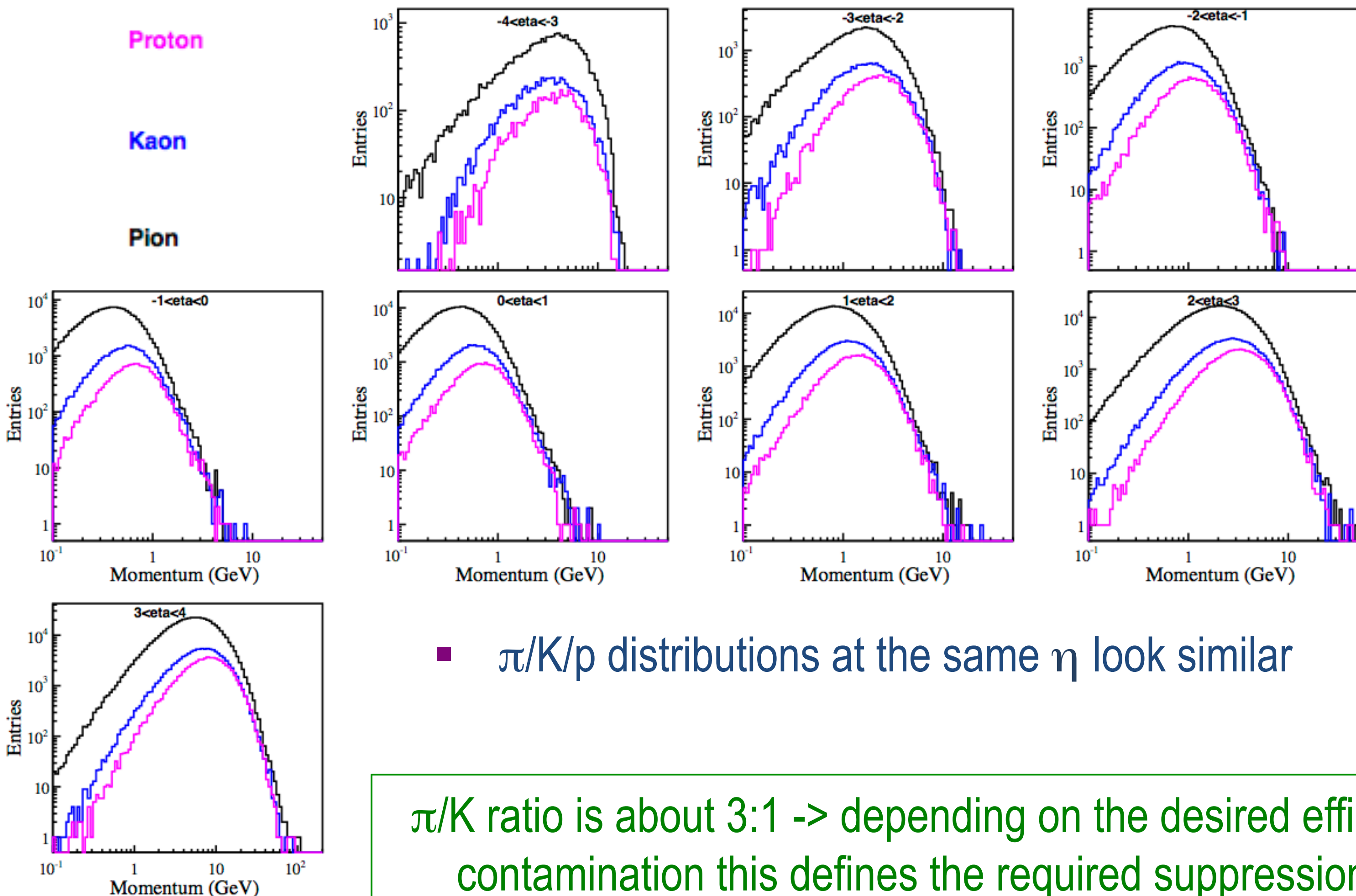


γ suppression:
the same η coverage for
tracking & Ecal

h^- suppression through E/p
$-3.5<\eta<-1$: 10:1 to 10^3:1
$-1<\eta<1$: 10^4:1

Relative pion/kaon/proton yields

20x250 GeV configuration; yields versus momentum in the $4 < \eta < 4$ range:



- π/K/p distributions at the same η look similar

π/K ratio is about 3:1 -> depending on the desired efficiency and contamination this defines the required suppression factors

Detector requirements (refined)

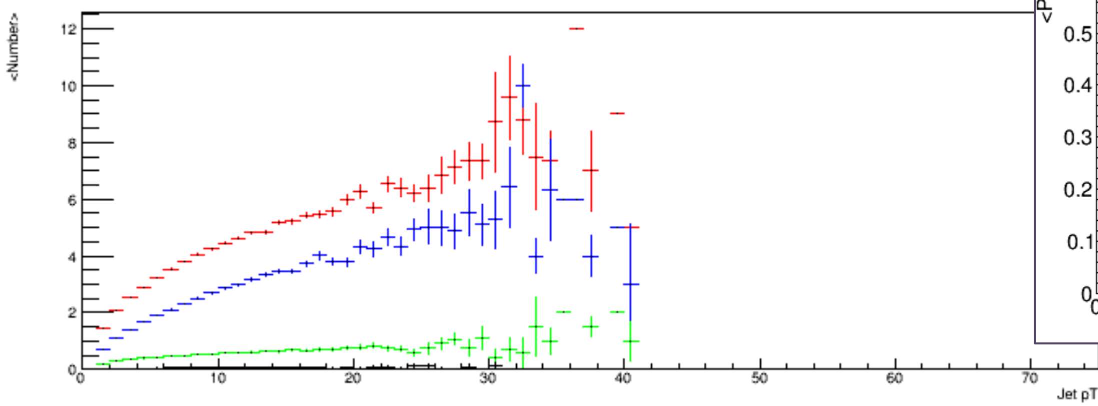
- $-3.5 < \eta < 3.5$ is sufficient for the main detector → try to get to $\eta = -4$ if possible
- Material budget of 5% X_0 is ok → anything above that: why bother?
- Momentum resolution on a (few) % level is fine → no need to do better at a cost of higher X/X_0
- Electron ID → $-3.5 < \eta < 1$; π suppression up to $1:10^4$
- π/K/p separation → suppression factors ~100 required (and momentum distributions are very η-dependent)
- Spatial resolution of primary vertex → ~10-20μm must be fine
- Jets → HCal at forward η needed; at mid-η - not!

Jets at mid-rapidities

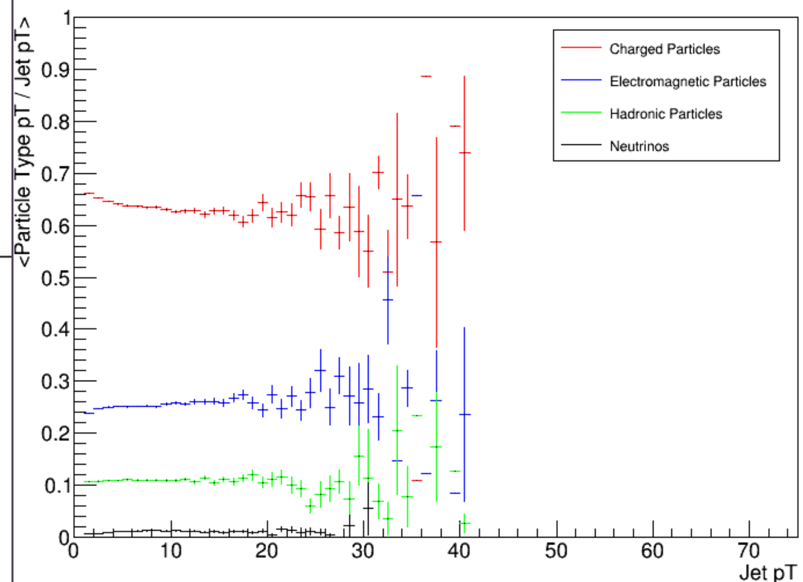
20x250 GeV; Q^2 [10 .. 100] GeV^2 ; $-1 < \eta < 1$

EIC jets at $|\eta|<1$ are "jetlets"

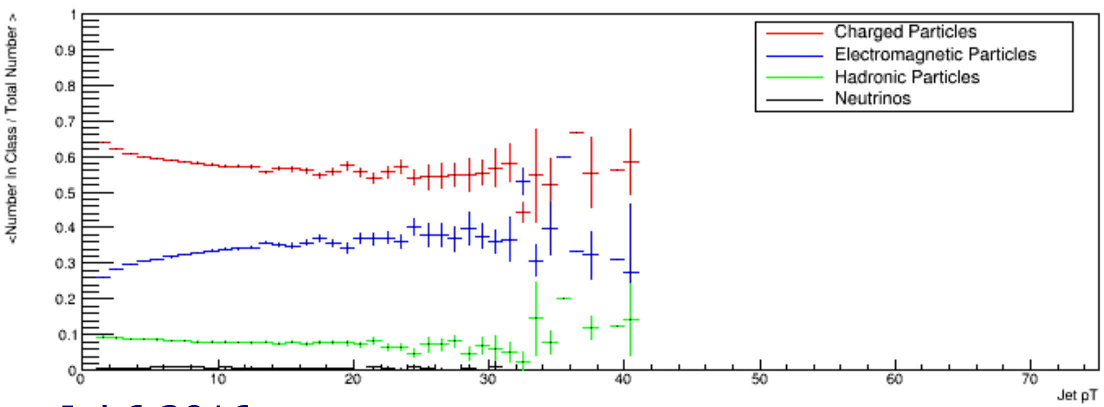
Absolute number of particles in each class



Fraction of jet P_t carried by different particles classes



Fractional number of particles in each class



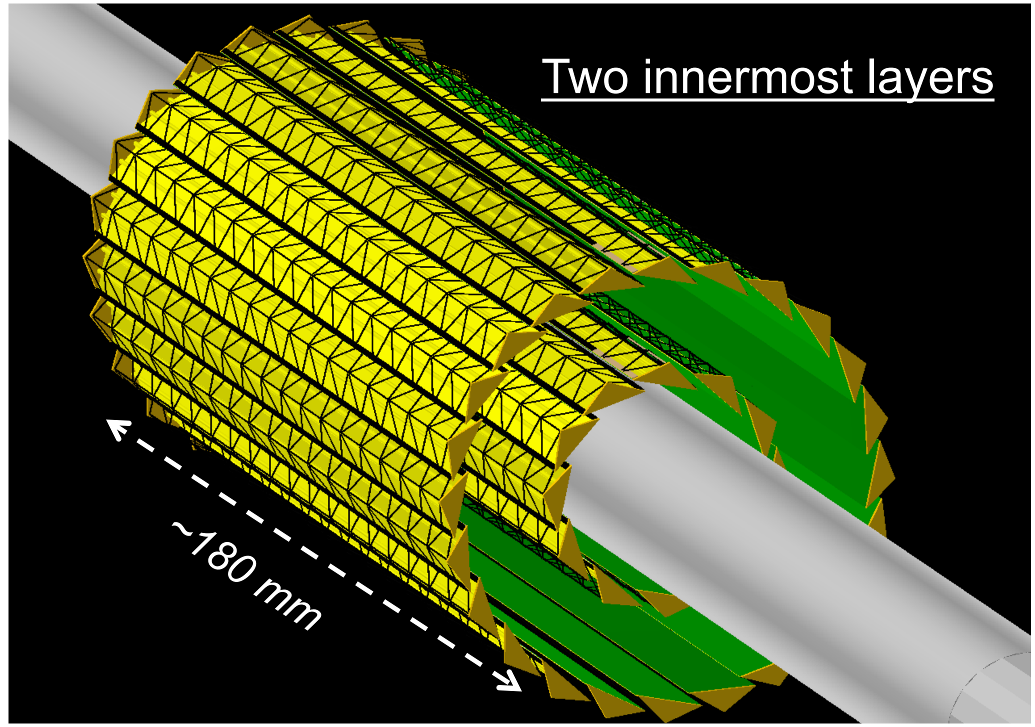
- Fraction of P_t carried by neutral hadrons is small
- No way ~50%/√E hadronic calorimeter energy resolution at <40 GeV/c can beat tracker momentum resolution

Reference tracker configuration

Silicon Vertex Tracker

Configuration similar to ALICE ITS design should work just fine (and simulation environment is pretty much set up and ready for design optimization work)

- 2x2 barrel layers with high resolution MAPS
- assume 20x20 μm^2 pixels and ~0.3% X_0 per layer



J. Phys. G: Nucl. Part. Phys. **41** (2014) 087002 The ALICE Collaboration

The prototype (ALICE ITS TDR page scan)

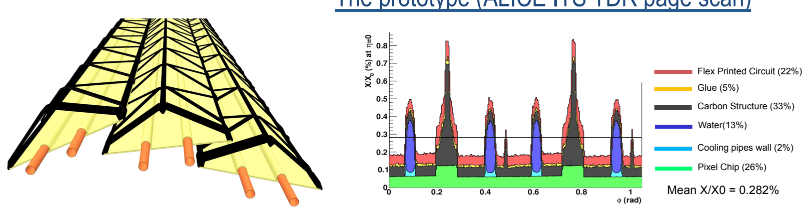
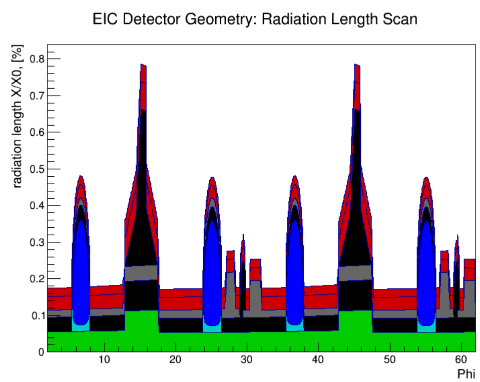


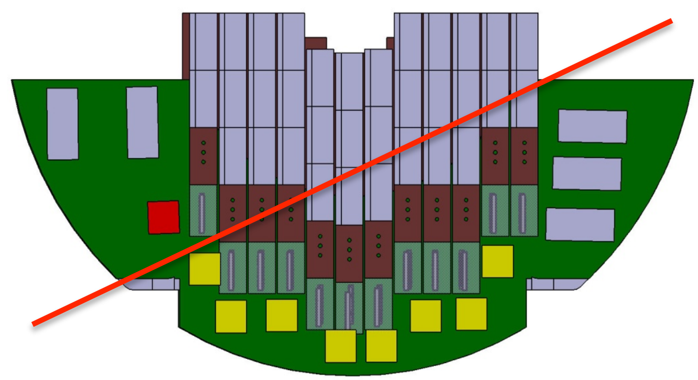
Figure 4.3: A detail of the Stave overlaps of the Inner Layers (left) and the corresponding material budget distribution (right). The highest peaks correspond to the overlap of the reinforced structures at the edges of the Space Frame, while the narrow spikes to the reinforcement at the upper vertex. The peaks around 0.5 % X_0 are due to the polyimide cooling pipes fully filled of water.



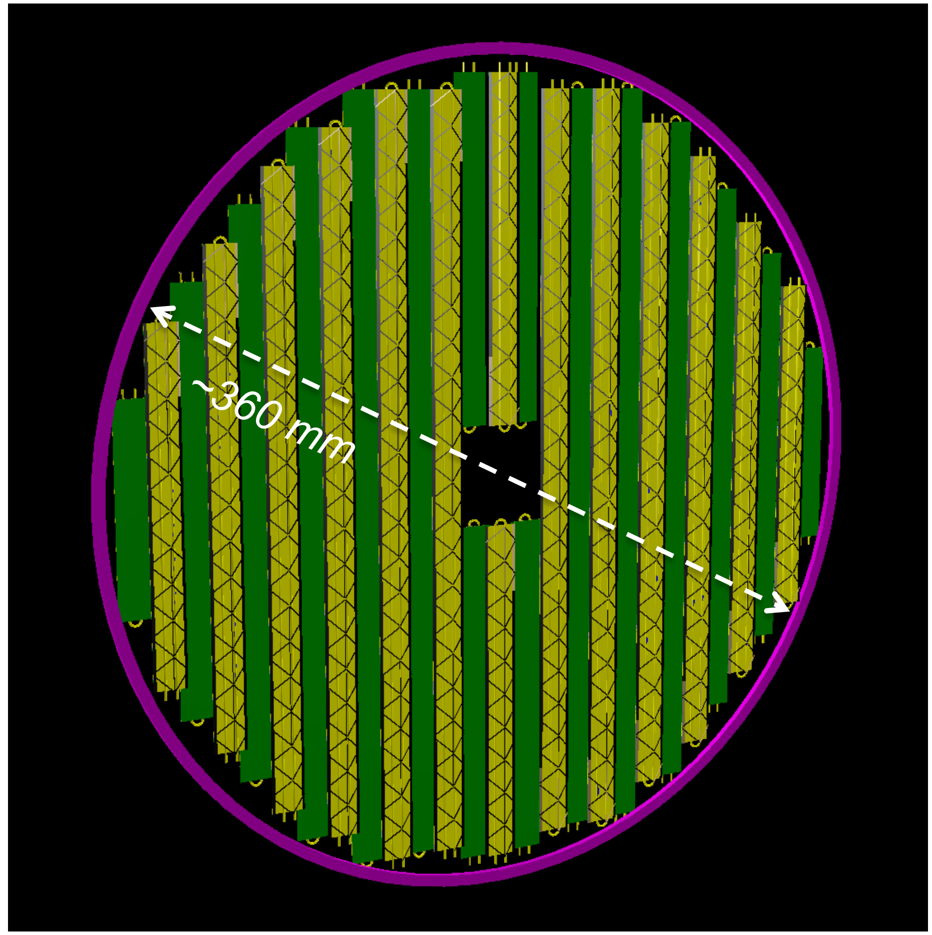
- EicRoot radiation length scan (single layer)

Forward & backward Silicon Trackers

- for now assume the same *a la ALICE ITS* building blocks (complete staves) as in the vertex tracker; 2x7 "discs" with [30 .. 180] mm radius



Also notice: ALICE MFT design "as is" won't work (no radial space!)

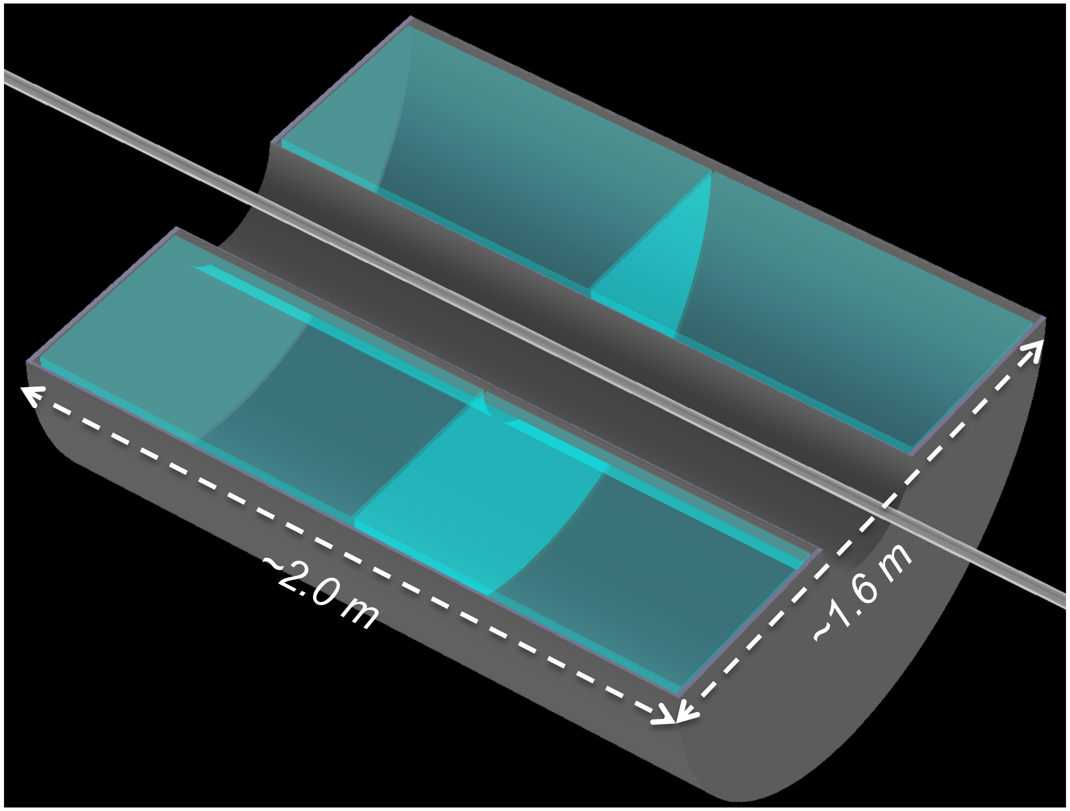


Design of this subsystem should clearly attract more attention (generic layout, material budget, cooling system type, support system, communications; also perhaps chip optimization (rolling shutter frequency increase, ...?)

TPC

- ~2m long; gas volume radius [225..775] mm
- 1.2% X/X_0 IFC, 4.0% X/X_0 OFC; 15.0% X/X_0 end-caps
- assume 5 mm long GEM pads and ~250 μm single point {rϕ} resolution for the max. drift distance of ~1m
- A gas mixture like T2K at ~250 V/cm (very small transverse dispersion in 3T field) will do the job

Pretty much in sync with sPHENIX prototype



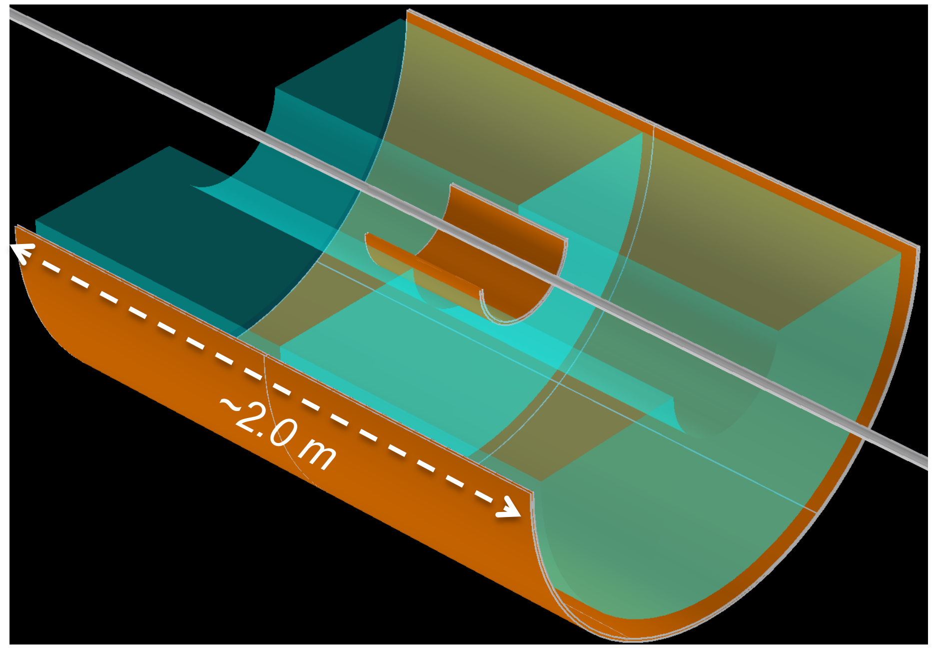
These days this is seen as a medium size and medium resolution TPC

Micromegas barrel tracker

- 4 layers; technology-driven azimuthal and longitudinal segmentation
- 2D readout with ~100 μm spatial resolution

Assume CLAS12 upgrade modules internal structure for now

Real life module (Saclay)



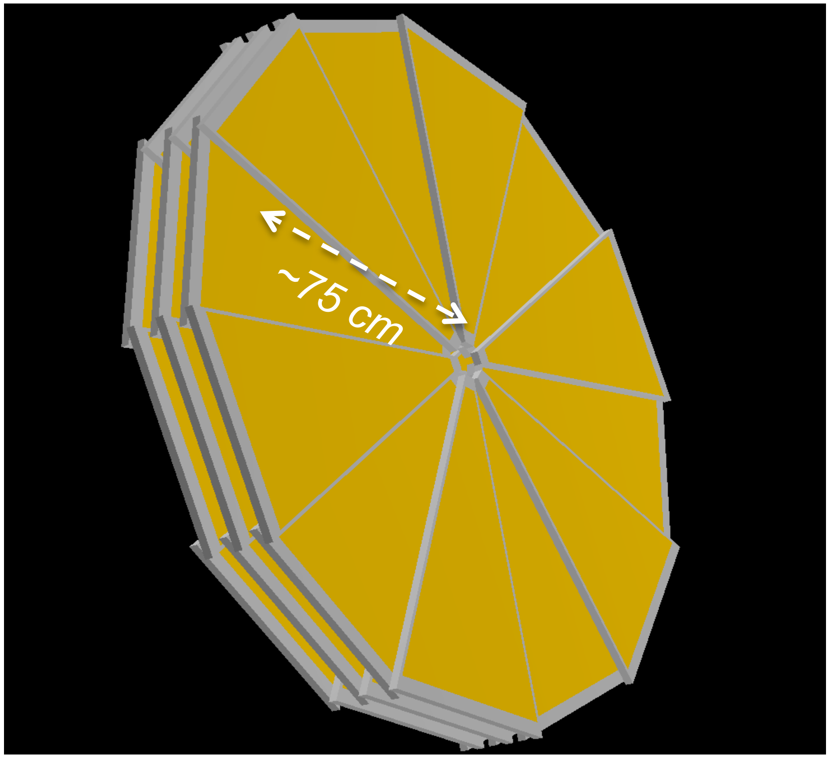
Size somewhat larger than CLAS12 modules needed; 2D-stereo readout?; high spatial resolution in 3T field; further material budget minimization (~0.5% X/X_0 per layer assumed for now)

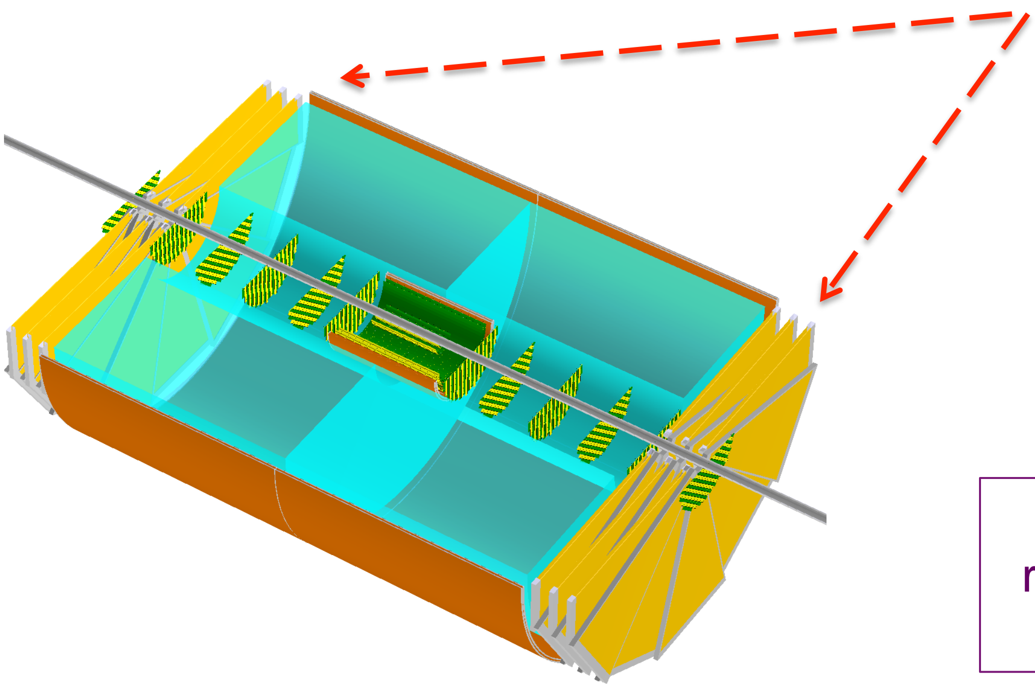
GEM endcap trackers

- 3 disks *behind* the TPC end-caps

Both ePHENIX and BeAST implementations assume that 50 μm {rφ} spatial resolution can be achieved

Assume SBS internal design





"Lightweight" and "large" are requirements for ePHENIX only (NOT for BeAST)

Tracker-related requirement summary

- MAPS detectors
  - Provide integrated FST+VST+BST solution (optimal layout, support, cooling, communications, …)
  - Consider further minimization of material budget (this is especially critical for e-going direction)
  - Consider non-planar chip arrangement on the staves (?)
  - A better chip development is appreciated (but going below 20μm pixel size is not really needed)

- TPC
  - As long as sPHENIX TPC is compliant with EIC needs (dimensions, inner field cage thickness, readout plane radial segmentation, design goal spatial resolution, …) we are happy with it ☺
  - Ion Back Flow: given small charged particle rates, is it really a problem for EIC running?
  - dE/dx resolution is of interest (sPHENIX TPC GEM stack is per design not optimized for it?)

Tracker-related requirement summary

- Micromegas
  - Large size lightweight (0.5% X/X_0 or less per layer) modules needed
  - 2D readout with 100μm or better resolution in 3T field is required

- GEMs
  - Establish high (~50μm or better) spatial resolution, possibly in a micro-TPC mode, for medium size (up to ~70-75cm) GEM modules
  - Larger modules (>1m) are needed for ePHENIX option only
  - Actually the other extreme (Weizmann small building blocks) looks pretty interesting
  - Minimization of material budget is also of interest for ePHENIX option only

  - Readout plane optimization: configuration with low channel count zigzag strips, small DNL and high enough resolution wanted (*but my personal opinion is biased here* ☺)
  - Development of a readout chip with large dynamic range and smaller time constant would be appreciated

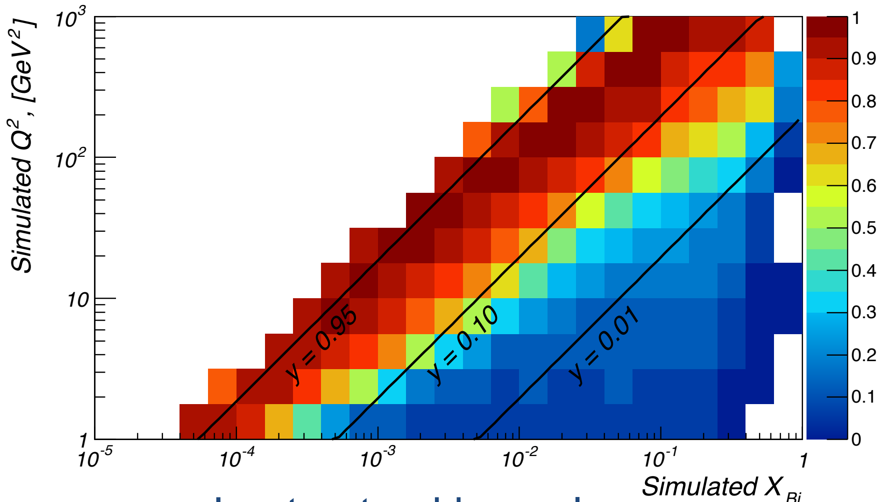
    -> these two points are valid for TPC-related R&D as well

Scattered lepton energy reconstruction

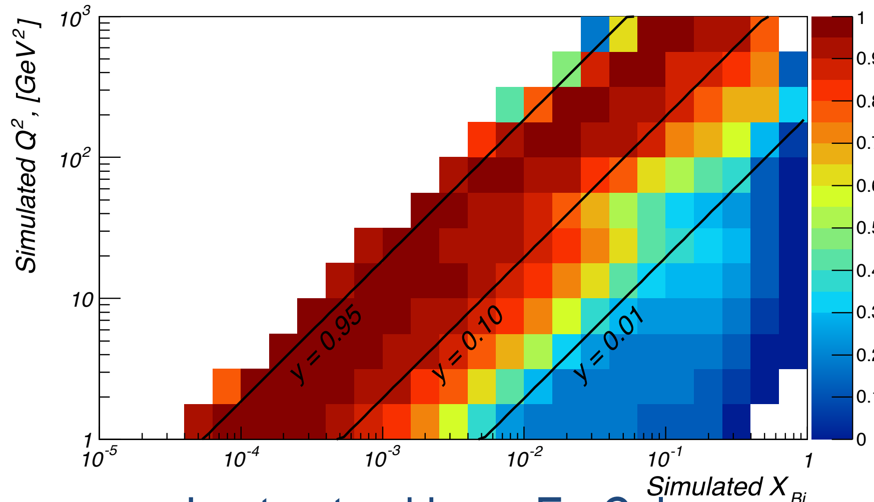
“Purity” in (x,Q^2) kinematic bins

→ a trivial observation: tracker momentum resolution rapidly degrades at backward rapidities; this clearly affects {x,Q^2} reconstruction quality

- A possible solution: use e/m calorimeter in addition to tracking
  - ~2%/√E energy resolution (and ~0 constant term) for $\eta < -2$ (PWO crystals)
  - ~7%/√E energy resolution for $-2 < \eta < 1$ (tungsten powder scint. fiber sampling towers)
- Consider “bremsstrahlung off ” case here for simplicity



Lepton tracking only



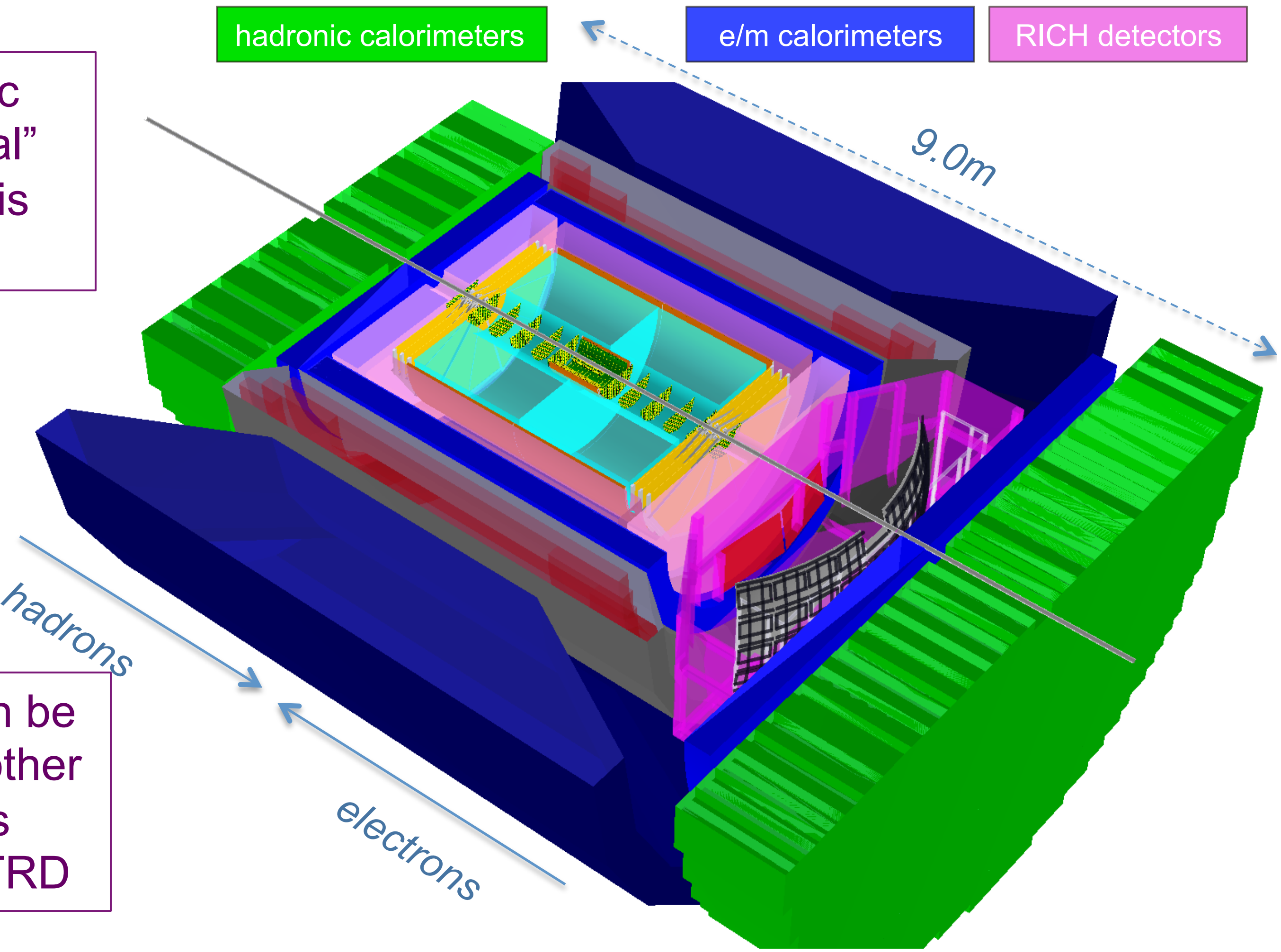
Lepton tracking + EmCal

High-resolution crystal calorimeter at very backward rapidities should definitely help to increase available ***y*** range

Scattered lepton identification

Reference detector layout

A detailed microscopic simulation of “e/p+HCal” electron identification is in progress



If needed, the setup can be appended at $\eta < -1$ by other electron ID detectors like preshower and/or TRD

silicon trackers | TPC | GEM trackers | Micromegas barrels | 3T solenoid cryostat | magnet yoke

EmCal requirement summary

- Crystal EmCal (*PWO a la CMS&PANDA?*) -> next talk by Tanja
  - ~2%/√E energy resolution should be enough (but clearly, the higher the better)
  - We are talking about covering ~1m^2 surface, at most

e$^-$ and γ energy measurement;
e/p electron ID

- Tungsten powder scintillating fiber EmCal -> next talk by Oleg
  - Compact readout development (without energy resolution degradation) is of the highest priority
  - Readout segmentation can be decided later and clearly can be different for different η
  - Flexibility in energy resolution range (driven by budget and available space) has to be maintained:
    - highest possible (~7%/√E) energy resolution in e-going direction (E/p is critical; space is available)
    - ~10%/√E energy resolution in the barrel must suffice (lack of radial space)
    - forward direction – requirements yet to be decided (and generally less demanding)
  - If we pursue proximity focusing RICH option for π/K/p separation at mid-rapidities, barrel EmCal must be placed at a bigger radius than anticipated before
  - 2D projectivity is not an EIC requirement

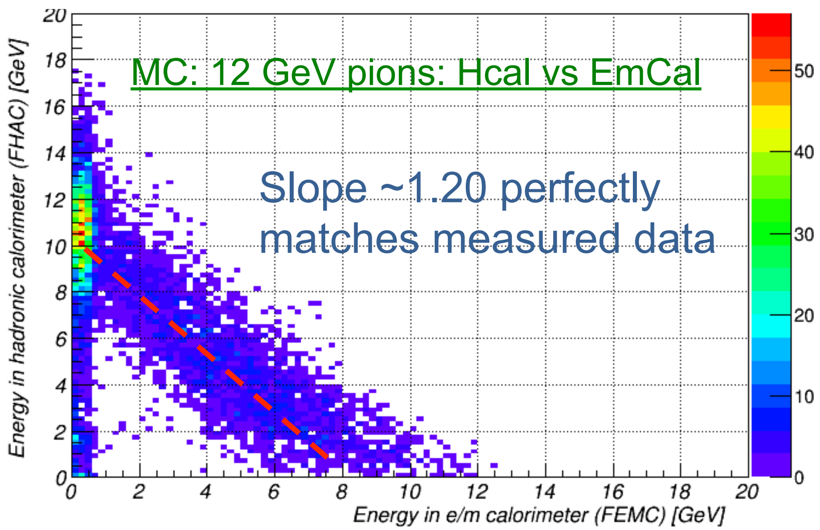
→ H1 : (7..12)%/√E+1%
→ ZEUS : 18%/√E+1%

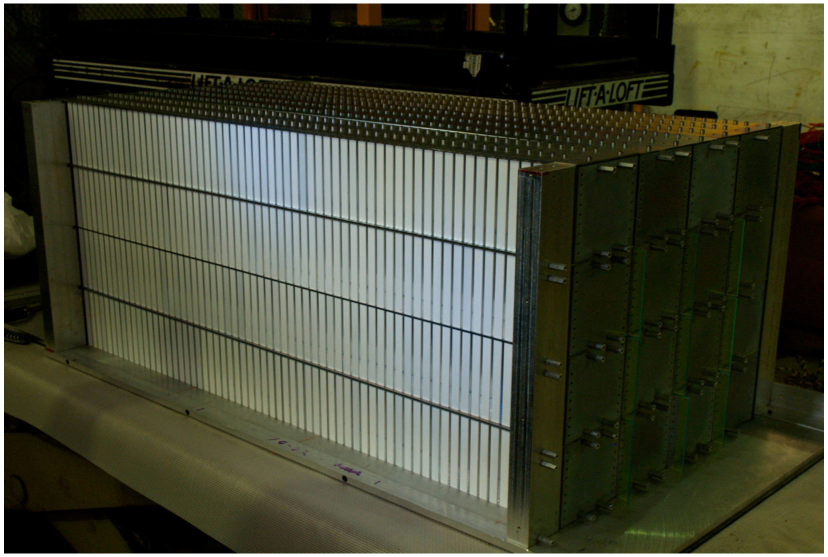
- SiPM readout validation in EIC environment (anomalous signals, neutron irradiation, …)
  -> this point is valid for other equipment as well (HCal, RICH)

HCal requirement summary

Electron identification in electron-going direction;
jet physics in the hadron-going direction

- Barrel HCal is NOT an EIC requirement





- Present design (sandwich with WLS plates) seems adequate
- ~50%/√E energy resolution looks fine
- Cost optimization may be required (use steel plates instead of lead?), but this has to be considered together with the solenoid return yoke design

π/K/p separation

General considerations

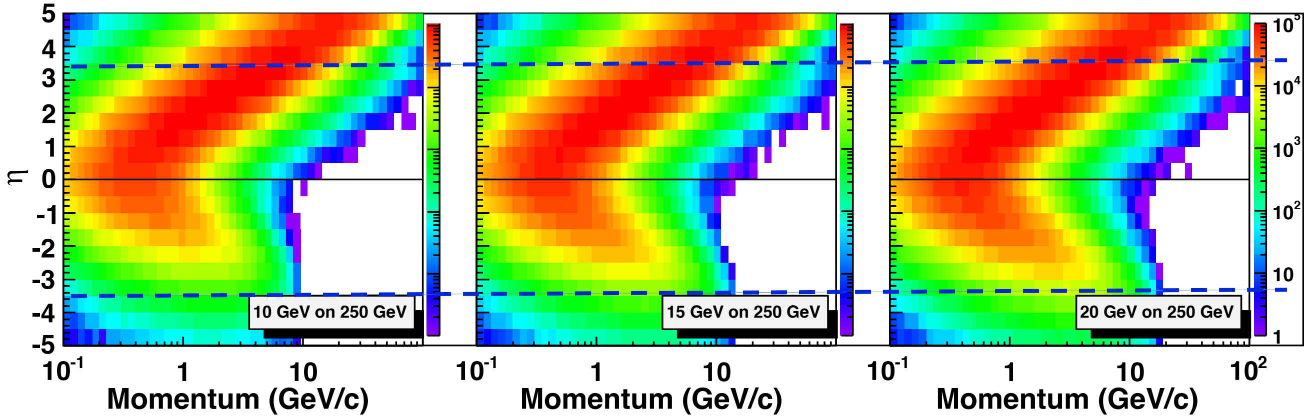
- Rely on various types of Cerenkov detectors as the main device for π/K/p separation
- EIC configuration is rather unique:
  - Potentially want to cover η range [-3.5 .. 3.5], *all* in a ~2-3T field of a compact solenoid:
    - Hard to use long (>1m or so) gas radiator in a (strongly non-homogeneous) fringe field
    - No way to shield the readout (so the options are very limited: GEMs, SiPMs, ..?)
- Based on relative yields conclude that suppression factors around 1:100 or better are needed for specific momentum ranges at given η values

  -> 3σ separation may be on a low end (?)

- Assume RICH can be supplemented by either TPC dE/dx (below ~1 GeV/c) or ToF (below ~1-2 GeV/c)

General considerations

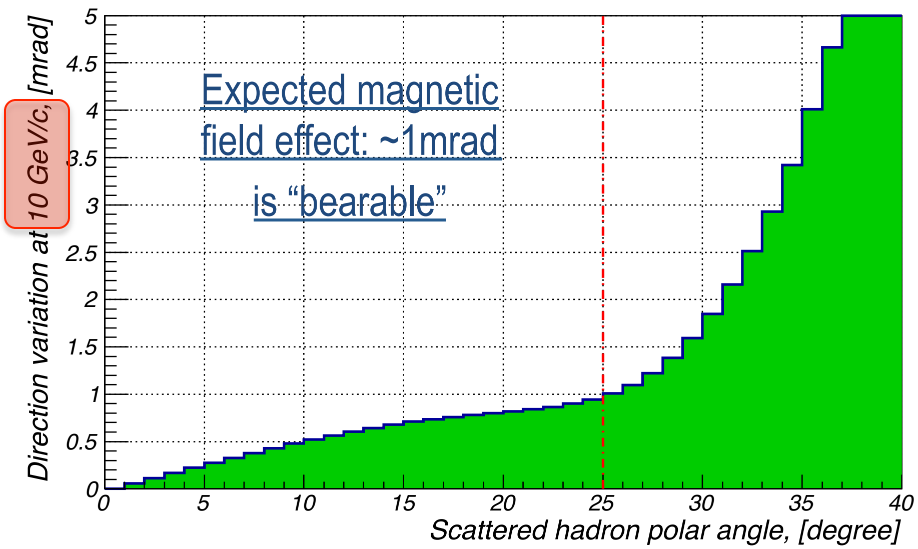
- SIDIS hadron momentum distributions: as high as ~50GeV/c, but a plenty below 1 GeV/c

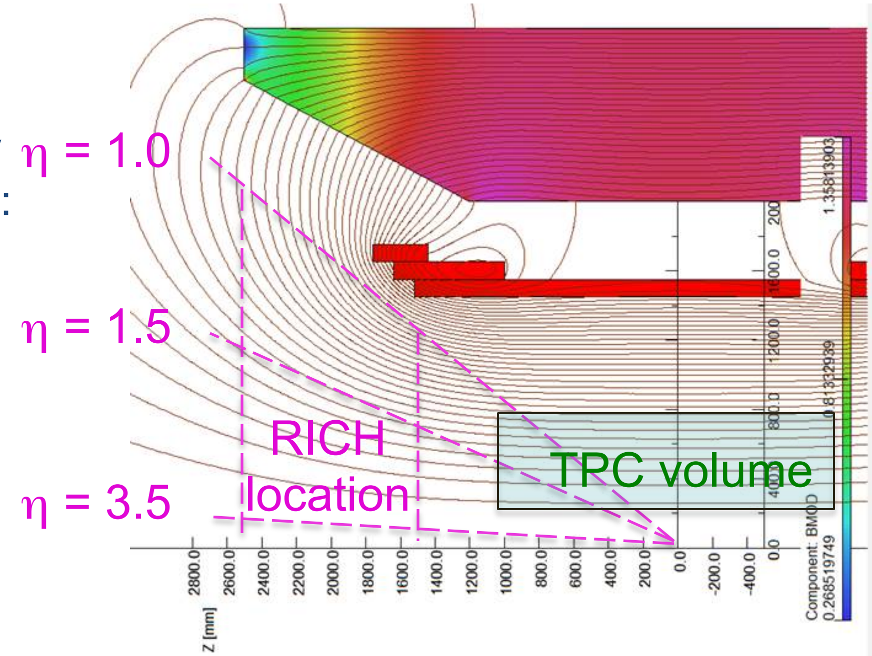


- To which extent can we use results of the very successful “CF_4 + GEM RICH R&D”?
  - No need for momenta above 50 GeV/c
  - Once CF_4 is chosen as gas radiator, there is a glaring hole in Kaon ID below ~17 GeV/c
  - GEM readout inconsistent with aerogel-based dual radiator concept

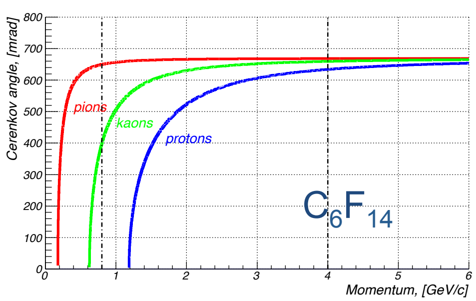
$0.02 #1: gas RICH at forward rapidities

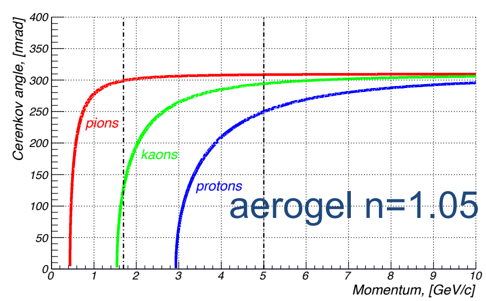
- Consider to use combination of solid (aerogel, C_6F_{14}?) and gas (C_4F_{10}?) radiators
- Make sure one can minimize bending effects by special “alignment” of fringe field magnetic lines:

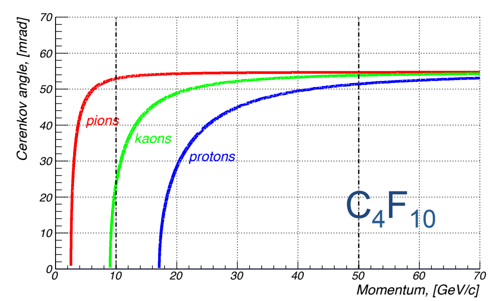




If needed, can we consider *three* radiators at once to cover full momentum range of roughly [<1 .. ~50] GeV/c?

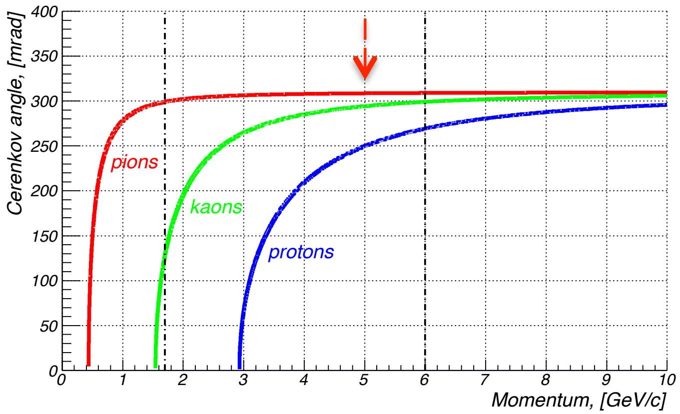






\$0.02 #2: proximity focusing RICH

NB: at 3T full track bending in aerogel volume is >5 mrad at 5 GeV/c!



Consider end-cap case in proximity-focusing configuration:

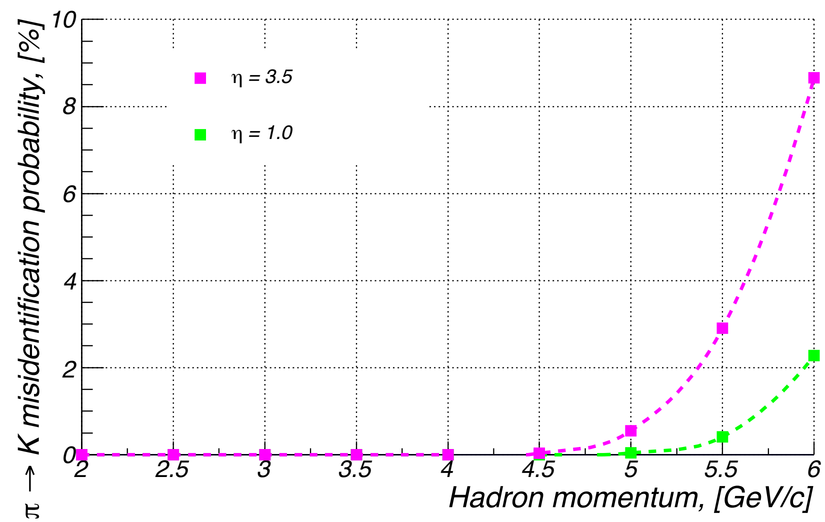
- 3cm thick aerogel; 20cm expansion volume
- $<n_0> = 1.05$
- ~5cm attenuation length
- SiPM array readout; 5mm^2 "pixel" size
- Assume on average 15 photons per ring at $\beta \sim 1$

Aerogel RICH R&D for Belle II upgrade

"Back-of-the-envelope" Monte-Carlo study:

- Constant $B_z \sim 3T$
- Asymmetric (ϕ-dependent) attenuation
- ϕ-dependent Cerenkov angle smearing in the field
- SiPM quantum efficiency $\varepsilon(\lambda)$ dependence
- Refractive index $n(\lambda)$ variation
- Emission point uncertainty (thick radiator)
- Finite readout board "pixel" size

- Root TMVA-based output evaluation



Require 95% kaon positive identification efficiency

Hadron PID requirement summary

- Lowest momentum in the whole η range: ALARA (but for sure <1 GeV/c)
- Highest momentum:
  - Forward η: up to ~50 GeV/c (at least for η range [1.5 .. 3.5])
  - Central η: up to ~3-4 GeV/c (anything wrong with C_6F_{14} in proximity focusing configuration?)
  - Backward η: up to ~5-6 GeV/c would suffice
- At most few % of π->K misidentification probability at 90-95% K efficiency

- Seemingly gas radiator RICH is limited to ~1m length in both BeAST and ePHENIX

- dE/dx capability of GEM-based TPC below 1 GeV/c is of interest at central η

- Reliable *complementary* cheap ToF-based π/K/p separation below 1-2 GeV/c seems to be preferential compared to *independent* ultra-high timing PID up to ~3-4 GeV/c?

Other PID-related considerations

- Would be interesting to see *detector combinations* with solid *numbers*
  - Say ~1:10^4 π suppression in electron ID is "broken down" into ~1:100 prf (TRD), ~1:20 (EmCal), ~1:5 (preshower) or whatever the detector combination is
  - Similar for e.g. RICH+ToF+TPC (over required momentum range) for π/K/p separation

-> individual detector requirements will become much more clear (and dual radiator RICH plots in the PID consortium report are a good example)

- Competitive comparison to existing solutions, e.g.:
  - LHCb RICH#1 with a suitable readout?
  - Belle II aerogel proximity focusing RICH with SiPMs?
  - Plain old HERMES TRD?

Thank you!